UNPUBLISHED PRELIMINARY DATA

DUKE UNIVERSITY

REPORT ON FEASIBILITY STUDY

OF LIQUID-METAL SWITCH

Prepared under Research Grant No. NsG 152-61, Supplement 2-62

Department of Electrical Engineering
College of Engineering
Duke University
Durham, North Carolina

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

The College of Engineering

REPORTS CONTROL No.________

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SUMMARY

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This is the final report of the feasibility study of the liquid-metal switch. The report discusses the theory and principles of operation of a liquid-metal switch. Factors influencing the selection of the liquid metal and several physical configurations are presented. Experimental results for one particular configuration are included.

Author

INTRODUCTION

With the space program providing the most immediate stimulus, a variety of unconventional means for the generation and processing of electrical energy are under development (1,2). Many of these newer means for the generation of electrical energy are intended either for the utilization of heat or light from the sun or the utilization of heat from a nuclear source of primary energy. It is interesting that almost all of the methods now under development for the generation of electrical energy are characterized by a direct-current output. Examples include thermoelectric converters, thermionic converters, solar cells, and fuel cells.

Though these devices differ in many respects, they share one important common characteristic: they provide a direct-current output at a very low voltage level. Thus, if these sources are to be used to provide power to a d-c to a-c inverter or a d-c to d-c converter, either enough of the low voltage generators must be connected in series so that the input voltage to the power-conditioning unit may be raised to a level which will enable the unit to perform efficiently, or the converter or inverter must be capable of efficient performance with a very low-voltage high-current input. The latter alternative, minimizing the number of generators connected in series, is quite often more attractive from the viewpoint of reliability.

It is largely the limitations imposed by the saturated voltage drop of available switching elements that establish the lowest practical input-voltage level at which converters may be operated. A number of static switching elements have been considered for this purpose (3). Special high-current tunnel diodes are presently being given particular attention for this purpose, and considerable work has been done by Marzolf (4) and Hanrahan (5) of the U. S. Naval Research Laboratory and by Storm and Shatuck (6) of the General Electric Company. The main advantages of these inverters appear to be their simplicity and the fact that the use of tunnel diodes allows the inverters to be operated at high frequencies. Inverters using tunnel diodes, however, are subject to some rather severe efficiency limitations because of the limitations which are inherent in the characteristics of presently available high-current tunnel diodes themselves (7). On a comparative basis between presently available switching elements, transistors appear to show the most promise (8). Several transistor manufacturers have recently developed special transistors with this application in mind.

However, semiconductor switching elements having, typically, on the order of 10^{19} carriers/cm^3 obviously are at a considerable disadvantage when contrasted to electromechanical switches in which the current path is composed entirely of metal having on the order of 10^{22} carriers/cm^3. Solely from the efficiency viewpoint, an excellent choice for the switching element for use in a low voltage converter would appear to be an electromechanical vibrator similar to those long in use in automobile radios, etc. in which a metal-to-metal contact is alternately opened and closed, thus making possible quite efficient low-voltage, high-current switching. However, the strenuous reliability requirements necessary for spacecraft usage have largely precluded the consideration of any of the presently available types of electromechanical, all-metallic switching elements.

LIQUID-METAL SWITCH

On possibility for attaining high reliability in a switch in which the conducting path is completely metallic is to use a liquid metal as the only physically moving macroscopic element of the switch and to utilize some phenomenon to cause the desired movement of the liquid without dependence upon gravitational or inertial forces. Though such a switch would not be "static" in the strictest sense of the word, it would not depend for its operation on mechanical movements of the switch capsule or its supporting members.

At least two modes of approaching the design of a liquid-metal switch have been suggested and studied. One such study (9) was undertaken under Air Force sponsorship by the Energy Conversion Group, Research Laboratory of Electronics, Massachusetts Institute of Technology. The approach used by this group depends on the periodic interruption of a constricted column of mercury caused both by heating, resulting from a localized region of very high current density, and the magnetic pinch effect. While an operable laboratory model of such a switching device was demonstrated by this group, their investigation was oriented primarily toward a consideration of the physical phenomena involved and did not focus much attention on the ultimately critical considerations of useful life time, reliability, efficiency, cost, and the size/weight and efficiency of compatible circuit configurations using this switch.

Another approach to the design of a liquid-metal switch, using different phenomena, was undertaken at Duke University. Electromagnetic forces rather than forces of thermal origin are used to cause the opening and closing of the switch contacts. One embodiment of such a switch was described in NASA patent disclosure No. 487 which was submitted to NASA June 29, 1962.

Since that date, additional work has been done to determine the feasibility of this device, and this report describes the results of this work and gives the conclusions which have been reached.

The problems involved in the investigation of a liquid-metal switch can be divided into two quite separate categories:

1) The problems of the conception and the design of an operable switching device suitable for use in a converter and including thermal, inertial, efficiency, size, weight, and reliability considerations, and

2) The materials problems which become involved when it becomes necessary to construct a reliable, high-performance switch.

The latter category of problems requires quite a different program of study than does the first and, in addition, requires a considerable amount of specialized and costly equipment.

The scope of this investigation at Duke was intentionally restricted to considerations in the first category listed above with the objective of developing several laboratory versions of the liquid-metal switch and of evaluating the potential utility of such devices without expenditures for highly specialized equipment to deal with the materials problems. The several laboratory models which were constructed and studied were intended to provide additional insight into various phenomena and to provide proof of principle. They were constructed of readily available commercial-grade materials and operated in the oxygen of the atmosphere, i.e., operated without any special precautions such as controlled atmospheres, component bake-out at high temperature, or hermetic sealing.

Desirable Low-Voltage Switch Characteristics

Any electrical system for providing either d-c to a-c inversion or d-c to d-c conversion, through the use of oscillatory phenomena, must involve one or more active elements, often referred to as switching elements (10). Conversely, given any element which can be made to perform as a switch, an electrical inversion or conversion network which will utilize this element can usually be designed. Whether or not the resulting system can truly be made practical for inversion or conversion depends largely on the limitations imposed by the switching element.

Generally speaking, the following characteristics are those of primary concern in determining the usefulness of a given type of switching element for static power conversion:

1) Current-carrying capacity in the conducting state
2) Forward voltage drop in the conducting state
3) Voltage-blocking ability in the non-conducting state
4) Leakage current in the non-conducting state
5) Temperature limitations
6) Life time and reliability
7) Frequency limitations, including limitations on cyclic rates of operation and limitations on speed of transition from "on" to "off" state and vice-versa
8) Manner of on/off control and the power gain provided by the element
9) Other characteristics, sometimes made especially important by particular applications, including (a) radiation tolerance, (b) size/weight, and (c) cost.

When the power source to a converter is to be characterized by a very low direct-voltage, correspondingly high currents are implied for the achievement of a given power level. Thus, characteristics (1) and (2) above become particularly significant in low voltage applications. The primary purpose of the liquid-metal switch investigation has been to study one possibility for the development of a switching element which can be made to have a very high current-carrying capability in the conducting state with a suitably low forward voltage drop and which will have utility in low-input-voltage power conversion equipment. Not only would such a switching element find uses in the space program where considerable attention is already focused on sources of electrical energy characterized by low-voltage direct-current outputs but it might well find industrial and consumer applications in the future as fuel cells begin to become economically feasible commercial power sources.

Principles Used in the Liquid-Metal Switch

The electrically controlled liquid switch operates on the principle that a current-carrying conductor experiences a force in a magnetic field. This force, as experienced by an electrical charge q moving with velocity $\overline{v}$ in a magnetic field $\overline{B}$, can be expressed by the vector relationship

(1) $$\overline{F} = q(\overline{v} \times \overline{B}).$$

For example, if in Figure 1, current is flowing in the conductor in the direction of the arrow $\bar{I}$ and the conductor lies in a magnetic field whose direction is indicated by the arrow $\bar{B}$, a force will act on the conductor in the direction of the arrow $\bar{F}$ whose direction is perpendicular to both the current and the magnetic field. If the direction of the current were reversed, the direction of the force would also be reversed.

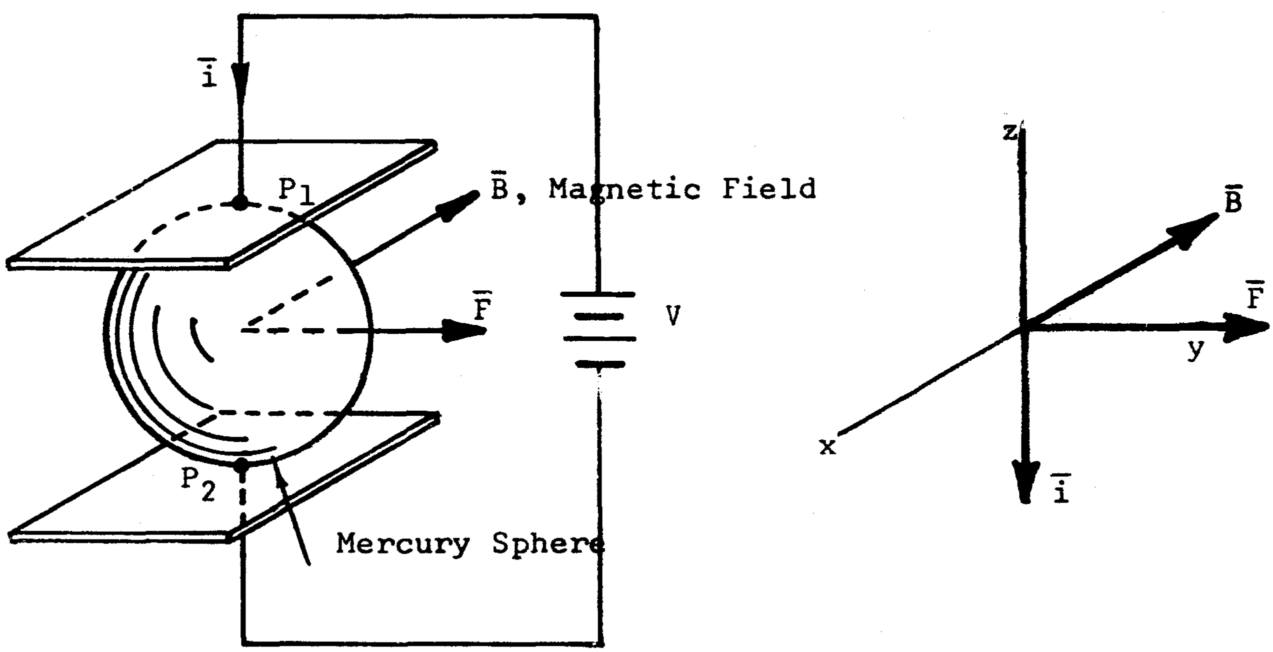

Figure 1 - The Field-Force Relationships Within The Liquid Metal Switch

In the types of switching elements herein described, current flowing in mercury in the presence of a magnetic field causes a force to be exerted on the mercury and this force causes a movement of the mercury within the switch cavity. Whether the switch is on or off at a given moment is determined by the location of the mercury with respect to contact surfaces within the switch cavity. A great many cavity shapes and contact surface configurations are possible. Various geometric configurations and restoring forces are used to give "on-off" operation.

The switches which were considered during this work can be divided into three general classes according to the manner in which the switching action is caused to occur.

1) In class one, the switch is designed such that current flowing through the liquid between a pair of contacts gives rise to an electromagnetic force which causes the liquid metal to move such as to break the circuit between the pair of contacts. As no current flows, this force becomes zero. The liquid metal is then restored to its original position by the surface tension of the liquid or other non-electromagnetic forces and the continuity of the circuit between the electrodes is re-established.

2) In class two, electromagnetic forces are used to control the movements of the liquid metal in both directions. In this class, the "control" contacts, whose purpose is related primarily to controlling the movements of the liquid, and the "switch" contacts, whose purpose is related to opening and closing a conductive path in an external circuit such as a converter circuit, may be the same contacts or separate pairs of contacts may be provided for each function.

3) In the third class of switch, the liquid metal is not caused to move back and forth in a straight path but, instead, is driven continuously around a short, closed path. This path may be circular or may have any of a variety of other configurations depending on the design of the particular switch. This approach to the design of a liquid switch appears to have certain advantages not inherent in the switches of class one and class two. Figure 2, 3, and 5 depict switches of this so-called race-track configuration, and these configurations are discussed in more detail in a later section.

The nature of the operation of all three of these classes of switches is such that a liquid metal with a high surface tension is desirable. Mercury was used in all of these experiments. The high surface tension and high conductivity of mercury make it an excellent choice in these two respects.

Commonly the amount of liquid metal within a switch cavity is kept quite small, e.g. an amount equivalent to a sphere of about 1/8 - inch diameter. Because of its high surface tension mercury globules of this size tend to assume a nearly spherical shape even under the forces of gravity. These characteristics become even more pronounced as the amount of liquid is made less.

These switches are used in low-input-voltage circuits such that they are not required to block voltages exceeding the ionization potential of the liquid-metal used (10.6 volts in the case of mercury). Since movement of mass on a macroscopic scale is inherently involved, such switches, though actuated by electromagnetic forces, will unavoidably have some sensitivity to gravitational and inertial forces, although it should be possible to minimize such sensitivity to the point that a very wide range of uses would be feasible.

Selection of the Liquid Metal

The characteristics of mercury and certain mercury alloys are compatible with the requirements of the liquid metal used in these switches. Largely due to its availability, mercury was used for all of the test switches built during this study. At atmospheric pressure mercury is a liquid over a range of approximately 400°C with a boiling point of 356°C and a melting point of -39°C. Important physical constants of mercury are listed in Table I.

TABLE I

CHARACTERISTICS OF MERCURY

Characteristic	Numerical Value	Remarks
Atomic Number	80	
Atomic Weight	200.61	
Valence	1, 2	
Melting Point	-38.87°C	sea level
Boiling Point	365.58°C	sea level
Specific Gravity	13.546 gm/c.c.	20°C
Specific Heat	0.032 - 0.033 cal/gm	liquid
Surface Tension	480.3 dynes/cm	0°C
	487 dynes/cm	15°C
Ionization Potential	10.39 volts	
Resistivity	94.07 μΩ-cm	0°C
	98.50 "	50°C
	103.25 "	100°C
	114.27 "	200°C
	113.5 "	350°C
Coefficient of Resistivity	0.00089	20°C

The mutual molecular attraction between mercury and nonmetallic and certain metallic materials is small, and consequently mercury does not wet these materials but forms a convex meniscus with a contact angle of 140 degrees. Non-wetting electrodes were used in each switch design. Suitable electrode materials are tungsten, molybdenum, platinum and iron or iron alloys. Pyrex glass and teflon were used as the nonconducting portions of the capsule construction. Teflon was used mainly because of ease in fabrication. Use of pyrex glass allowed observation of the movement of the mercury.

As in any active metal, mercury has a tendency to form an oxide, particularly in the presence of an electrical arc. This oxide forms on the surface of the liquid, causing the normal mirror-like surface to be replaced by a greyish wrinkled skin. This coating increases the contact resistance of the mercury, causes the mercury to tend to stick to the electrodes and capsule, and may prevent the mercury from remaining a single globule. Under these conditions small balls of mercury are often observed on the surface of the larger globule. This prevents the proper functioning of the switch.

VERIFICATION OF CONCEPTS - EXPERIMENTAL RESULTS

As mentioned previously, the possible configurations of the liquid-metal switch which were considered can be subdivided into three classes according to the nature of the forces which are utilized to cause the cyclic displacements of the mercury droplet within the switch cavity and according to the manner in which these displacements cause the interruption and completion of the main current path through the switch. Briefly, these three general classes are: (1) Class one, in which an electromagnetic force resulting from current flowing through the mercury droplet causes the movements of the droplet which open the switch, and in which the restoring forces which return the droplet to its original position so as to again establish a current path through the switch are non-electromagnetic in nature and might depend upon, for example, the surface tension of the droplet itself, (2) Class two, in which both the forces which cause the original displacement and the restoring forces are electromagnetic forces, and (3) Class three in which the mercury droplet is not cyclically displaced back and forth in a straight path but is driven continuously around a short closed path such as a circle or oval.

Although the physical configurations of these electrically driven liquid switches are typically quite simple, analytical treatment and predictions of their behavior are quite difficult. Reasons for this become apparent when one observes the cyclic movement of the droplet of a working model with a high-frequency strobotac. The overall movements of the mercury droplet are seen to involve many complex superimposed motions. Resonance phenomena, turbulence, surface tension, cavity geometry, the magnitude of the displacement forces, etc. each contribute in manners which are difficult to define quantitatively and which are highly nonlinear in their effects. Thus, it was considerably easier , in this limited feasibility study, to attempt to aquire meaningful data concerning optimum operative frequencies, driving power requirements, effects of various geometries, etc. through the construction and modification of experimental models rather than through complex techniques of mathematical analysis involving, at best, many rough approximations.

No truly high-current switching elements were constructed; most of the experimentation was done in the 1-5 ampere range. The necessary magnetic field was provided by a permanent magnet with a field of approximately 2,000 gauss. Commercial grade (0.005 % purity) mercury was used and all testing was done in an air atmosphere, and, therefore, each test was limited in time duration by oxidation of the mercury.

Fabrication of the test switches was a major task even though only rather crude models were built. This was principally because of the small physical geometrics involved and the necessarily minute dimensional tolerances. As mentioned previously, no attempt was made to bake out the switch capsules and/or fill them with hydrogen in an attempt to reduce contamination of the mercury and the contact surfaces. As would be expected, progressive oxidation of the mercury droplet was apparent during all tests of such switches, particularly when the switch became heated or when a particular switch design exhibited considerable arcing. Typically the oxidation of the droplet during testing in an air atmosphere made it necessary to limit the duration of such tests to about five minutes, after which it was necessary to clean the switch electrodes and replace the oxidized droplet of mercury.

Certain characteristics were common to all of the configurations which were tested or considered conceptually:

1) The maximum frequency attainable with these types of switches varies inversely with the volume of mercury which is cyclically displaced. On the other hand, the current-carrying capacity of the switches decreases as the volume of mercury is made smaller. Experimental models of various switch configurations were operable in the range from 15 to 1000 cps but the switches which could perform in the 200 to 1000 cps range used balls of mercury on the order of 1 mm in diameter and were generally low-current devices, e.g. 0.5 to 2.0 amps.

2) Since high frequency operation (above 15 cps) dictates physically small switches, heating of the switch is to be expected at high current levels. Heat sinking techniques appear necessary on high-current, "high-frequency" switches.

3) Pronounced resonance effects are encountered with these switches, since they involve cyclic movements of small globules of mercury which behave in an "elastic" fashion under the effects of surface tension. Although the various test switches could be operated at frequencies other than their natural resonant frequencies, driving power, i.e., the power required to cycle the switch on and off, is always found to be significantly less at or near a natural resonant frequency.

4) Using mercury globules having volumes equal to or less than that of a sphere having a diameter of 3 millimeters, no difficulties were encountered in any of the test switches with the mercury globule not remaining intact, i.e. not fragmenting, during any modes of switch operation. However, in applications which would require the switch to be operated while subjected to externally imposed high levels of shock and vibration, the possibility of fragmentation of the small mercury droplet apparently would be a serious problem.

Racetrack Congiguration

Figure 2 depicts a liquid-metal switch in which the mercury droplet is cycled continuously around a short closed path, and which will be referred to hereafter as the "racetrack configuration". Electromagnetic forces, as previously discussed, drive the mercury around the track, and inertial forces, during the traversing of the curved portions of the path, cause the interruption of the current path from the inner to the outer electrode (shaded in Figure 2). It was this configuration that provided the best liquid-switch performance obtained during the feasibility study, and its characteristics and limitations, as described in this section, are generally illustrative of the characteristics and limitations which are inherent in the basic electromagnetically-actuated liquid-metal switch concept.

The switch of Figure 2 is operated in a magnetic field such that the direction of the field would be into (or out of) the paper in Figure 2; i.e., perpendicular to the direction of the current flow which is from the inner electrode (shaded in Figure 2) to the outer electrode (also shaded). According to Equation 1 this current perpendicular to the field causes an electromagnetic force to act on the mercury droplet, and it is this force which drives the droplet around the track.

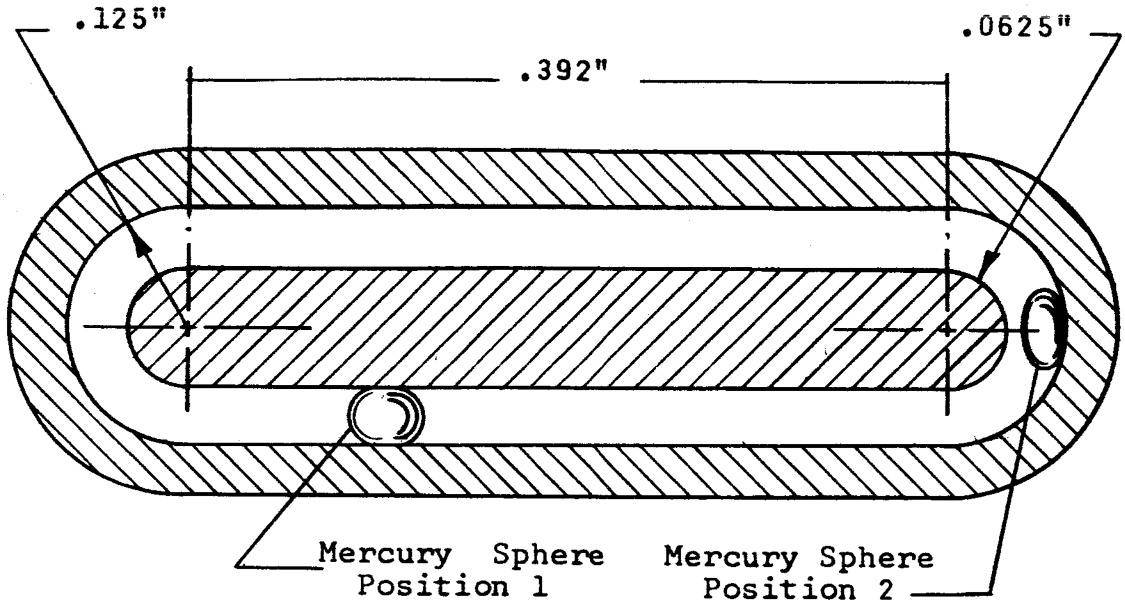

Figure 2 - Magnetic-Inertial Liquid Metal Switch

The large surface tension of the small mercury droplet is used to good advantage in the switch of Figure 2. While the droplet is in the straight portion of the path, it tries to assume a nearly spherical shape (tends to minimize its surface area), and therefore simultaneously presses against the inner and outer electrodes. This situation is illustrated by the mercury droplet in position 1 in Figure 2.

However, as the rapidly moving mercury droplet enters a curved portion of the track, it will be deformed by the inertial forces which suddenly begin to act upon it. The result is that the droplet becomes somewhat flattened against the outer electrode and no longer makes contact with the inner electrode. This is depicted by the droplet shown in position 2 of Figure 2.

Thus, the "on" time of the switch corresponds roughly to the length of time required for the droplet to travel the length of a straight portion of the switch and the "off" time corresponds roughly to the length of time required to travel the length of a curved portion. The switch of Figure 2 turns on and off twice for each time the droplet makes a complete cycle. The speed of the droplet, and therefore the frequency of switching, is directly dependent upon the magnitude of the current through the switch and, therefore, varies with load.

Actually, after the droplet leaves a curved portion of the track and again enters a straight portion, a finite period of time is required for surface-tension forces to cause the droplet to regain the more spherical shape which will again allow it to contact the inner and the outer electrode simultaneously. The larger the droplet and the track dimensions, the longer will be this lag time or time required for the droplet to again contact both electrodes after emerging flattened from a curved portion. It is this phenomenon which dictates the frequency limits for a particular switch design. Also, it is this phenomenon which causes the conflict between the design objectives of high-frequency operation and the design objectives of large current carrying capacity. The larger the mercury droplet, the less effective and fast acting are the surface tension effects which are necessary in controlling the shape of the droplet during the cyclic operation of the switch.

In order to increase the current-carrying capability of such a switch without sacrificing in operating frequency, if is necessary to operate several small units in parallel rather than to attempt to use a single larger switch. If these parallel units are made to be very nearly identical in construction, it is found that they tend to synchronize in their switching so as to give the external electrical characteristics of a single switch. This may be illustrated by considering two race track switches operating in parallel. Suppose one droplet reaches the curved portion of its path while the droplet of the other switch is still in a straight portion. When the current path through the first switch is interrupted, the current through the second switch is suddenly increased, and the droplet of the second switch will have a higher average current and a resulting higher velocity. Ultimately, therefore, the droplets of paralleled switches will operate either in phase or 180° out of phase with each other.

Figure 3 shows a photograph of a test model of a racetrack-configuration mercury switch. This switch has the dimensions indicated in Figure 2. The mercury droplet has a volume approximately equal to that of sphere with a 2.0 mm. diameter, and in Figure 3 this droplet can be seen in one of the straight parts of its track.

Figure 4 shows a typical waveshape of the current flow through the switch of Figure 3 during operation. The optimum cyclic frequency for this switch, determined in large part by resonant effects resulting from the surface-tension restoring forces, was approximately 30 cycles per second (cps). Above and below this frequency, switching became progressively more erratic. The waveform of Figure 4 shows the operation of this switch at 30 cps and, even at this natural frequency, considerable noise can be seen in the current waveform. This is caused primarily by the

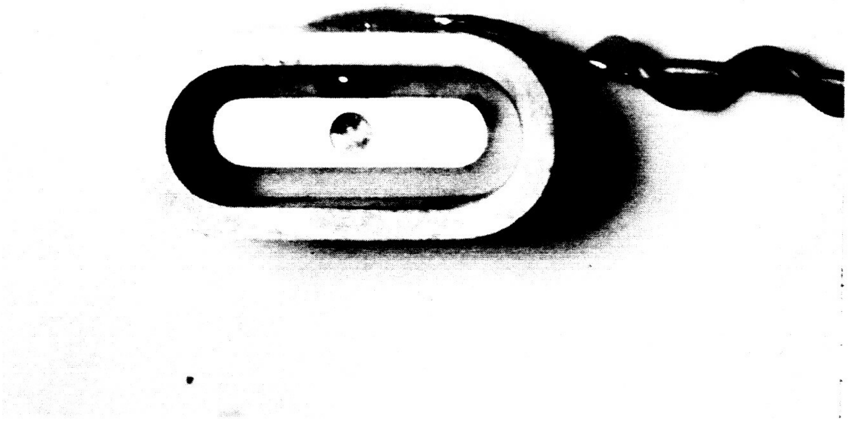

Figure 3 - Photograph of the Test Model of the Race-Track Configuration.

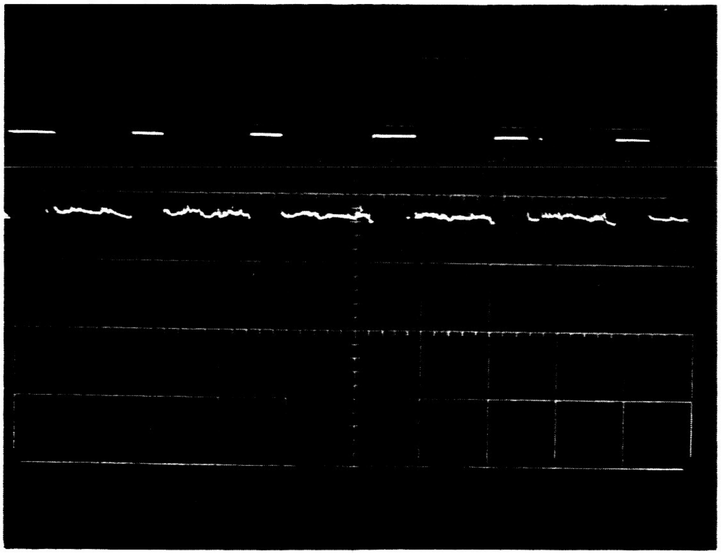

Figure 4 - A Typical Waveform of the Current Through the Mercury Switch Shown in Figure 3; the Erratic Portions of the Waveform Are the ON Interval.

Vertical Scale: 1 amp/division
Horizontal Scale: 20 millisec/division

dynamic behavior of the mercury droplet as it travels at a rate of about 90 centimeters per second around the track and is alternately flattened by inertial forces and then allowed to again assume a more nearly spherical shape. Using a strobotac, this droplet was observed to have many superimposed modes of motion. This turbulence along with dirt and irregularities in the surface of the electrodes causes the electrical contact during the conducting intervals to be somewhat erratic.

This model was operated with a resistive load continuously for four hours unsealed in an air atmosphere — considerably longer than had been achieved with other types of configurations. Gradually, during each test, the surface of the mercury sphere and the contact areas of the electrodes became contaminated and operation ceased. As has previously been mentioned, it is expected that with proper facilities such a switch could be baked out and sealed in a hydrogen atmosphere and that, by doing this and using highly pure mercury, such a switch could be made to operate for reasonably long periods of time. Ultimate limits on the life time of such a switch are difficult to estimate; past experience with conventional mercury switches is of little guidance because these conventional switches are mechanically actuated and ordinarily are employed at relatively high voltage levels. However, it would not be expected that these switches would become competitive with low-voltage switching transistors insofar as lifetime and reliability are concerned.

A modification of this basic design, shown in Figure 5, eliminates several of the disadvantages of this switch. The improved version uses a circular racetrack, operates at a lower mercury-sphere velocity, and has a higher frequency of operation which can be made independent of the load current.

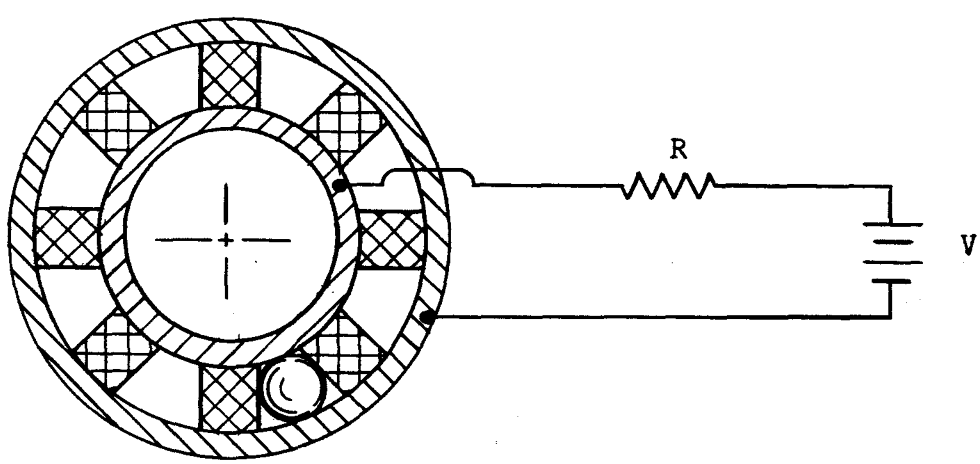

Figure 5 - Load Independent Liquid-Metal Switch.

This switch uses a separate current path for the load and control currents. The control circuit is essentially the same as the previous configuration, except that the velocity of the sphere is such as to allow continuous contact with the electrodes. This means the current is constant, the force on the sphere is constant, and consequently its velocity is constant. The control current can also be adjusted to reduce the "turbulence" of the motion.

Switching is accomplished by using many additional electrodes (cross-hatched in Figure 5) perpendicular to the continuous control electrodes. The load current passing through these electrodes is alternately interrupted as the mercury sphere makes and breaks contact with these electrodes. Furthermore the load current passes through the mercury sphere in a direction parallel to the magnetic field, and from Equation (1) the force on the sphere is zero. Consequently, the frequency of the switch is completely independent of the load current and is determined by the size and spacing of the switching electrodes once the constant frequency for a particular sphere size has been established. The multi-switching electrodes are adaptable to various wiring schemes including multiphase operation.

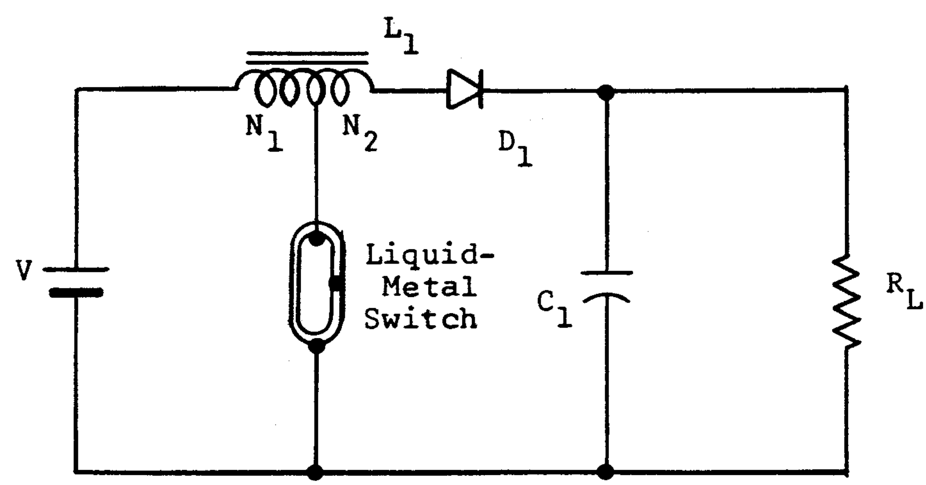

Figure 6 - Converter Circuit Using Liquid-Metal Switch

Figure 6 shows a very simple d-c to d-c converter in which a racetrack-configuration liquid-metal switch was successfully tested. Briefly this circuit operates as follows. As the mercury droplet traverses a straight portion of its path, the switch is made conducting and current flows from the battery through winding N_1 on the inductor and through the switch. Diode D_1 is reverse biased and energy is stored in the inductor. Then when the droplet enters a curved portion of its path, the switch becomes nonconducting. The magnetomotive force on the core of the inductor cannot be discontinuous, so, when the switch opens, current suddenly begins to flow through windings N_1 and N_2 in series and through D_1 to capacitor C_1 and the load R_L. The winding on the inductor is tapped as indicated because it was desired to provide a voltage step-up from approximately 1 volt at the source to approximately 28 volts at the load without requiring the mercury switch to block more than twice the supply voltage in the nonconducting state. Testing of this converter was confined to a mere demonstration of the fact that the racetrack-configuration mercury switch could, in fact, be used in a simple circuit for accomplishing a relatively large voltage step-up.

CONCLUSIONS

This investigation was undertaken at a time when it was uncertain as to whether or not suitable low-voltage transistors would be developed for use in very-low-input-voltage converters. The object of this study was to investigate in a preliminary manner the feasibility of designing and building liquid-metal switching elements which would have utility as the low-voltage high-current switch necessary in low-input-voltage converters. This study was concerned with an examination of the technical feasibility of such elements rather than with constructing usable devices, and no investment was made in the special purpose equipment which would be necessary to construct a high performance prototype. The conclusions which have been reached are not favorable, although it has been demonstrated that such switches can be constructed and, in fact, operated in converters.

The four primary disadvantages of this switch, insofar as aerospace uses are concerned are: (1) It has severe frequency limitations which make it unsuited for making possible lightweight converters, (2) It requires a magnetic field for its operation and this implies added weight, (3) It is subject to erratic operation during periods of high shock and vibration, and (4) Because it must be sealed in order to be operated in a vacumm and because of chemical effects involving heating, arcing, deterioration and contamination of the mercury and the switch electrodes, the life-time and reliability of such an element probably can not be made competitive with that of a transistor.

However, this type of switching element does offer some characteristics which are quite different from those of transistors. One of these characteristics is its insensitivity to radiation. Also, it should be possible to operate such a switch in a 300°C environment.

In certain situations, a low switching frequency and relatively short lifetime might not be of critical significance. For example, as fuel cells begin to be used commercially, it might be possible that an inexpensive electromagnetically-driven liquid-metal switch would find considerable utility.

It has been suggested also that the principles involved in the liquid-metal switch might be applied to a re-settable circuit breaker for use in spacecraft. Certainly such a circuit breaker is feasible insofar as electrical operation is concerned. However, the necessity for the magnetic field with associated weight problems and the formidable materials problems which must be investigated in order to assure long-term reliability of such a circuit breaker are discouraging considerations. Also, such a circuit breaker would be subject to inertial forces and possible malfunction therefrom.

It is not recommended that work on the liquid-metal switch be pursued any further. No further work is planned at Duke. If unforeseen special needs should arise at some future time which would indicate a need for a usable device incorporating these principles, it is suggested that the group which undertakes this task be a group which is primarily materials oriented. The problems of materials and fabrication and of assuring long lifetimes are the primary problems which might block successful application of these principles to a specialized task.

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Report on Feasibility Study of Liquid-Metal Switch

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ABSTRACT

Many of the newer devices for converting heat, light, and chemical energy to electrical energy are characterized by a very low voltage, direct-current output.

One possible type of low-voltage switching element for power conditioning systems to be used with such sources is a switch consisting of suitable contacts within a small enclosure in which a liquid metal such as mercury is cyclically displaced so as to alternately open and close the current path between certain contacts. Such a switch can be actuated electromagnetically, i.e. without dependance on gravitational or inertial forces or upon movements of the switch container, by subjecting the switch to a magnetic field and depending on the forces resulting from currents through the liquid metal to produce the desired movements of the liquid metal within the switch cavity.

This report concerns a limited feasibility study of this type of switching element. Various configurations and operating principles have been explored and such a switch has been operated in a d-c to d-c converter. The principal difficulties with this type of switching element would appear to be its rather low optimum frequency of operation (on the order of 100 cycles per second), and the thorny materials problems associated with achieving adequate operating lifetimes and reliability.